DESIGN OF PERSONAL AIR BAG SPINAL PROTECTION DEVICE

Brian L. Crowell[1], **Brian A. Stalcup**[2], **Daniel W. Stinemates**[3]

[1]Dept. of Civil Engineering, Stanford Univ., CA, 94305
[2]Dept. of Mechanical Engineering, Univ. of Houston, TX, 77204
[3]Dept. of Mechanical Engineering, Georgia Inst. of Tech., Atlanta, GA, 30332

ABSTRACT

Each year there are approximately 11,000 cases of spinal injuries that result in partial or complete paralysis. Significant portions of these cases are the result of sports related injuries that possibly could have been prevented with proper protection. The project undertaken was a preliminary investigation of the feasibility of a personal air bag spinal trauma protection device. A mock torso was constructed with wood, instrumented and subjected to a 1-meter drop. The impact accelerations were measured for trials with and without a prototype air bag attached to the mock torso. Using finite element commercial code ABAQUS/Explicit a model of the mock torso was subjected to a simulated 1-meter drop. The model was refined to match the results from the experimental drops without an air bag. Then the analysis was performed with springs and dampers inserted to simulate the air bag.

1 INTRODUCTION

The brain and the spinal cord together are called the Central Nervous System (CNS). The brain is the center of our thoughts, the interpreter of our external environment, and the origin of control over our conscious/unconscious movements. Like a central computer, the brain takes in information sent to it by our eyes, ears, nose, tongue, and skin. In addition to these five senses, the brain also receives information from internal organs. In order for the brain to receive and integrate messages from the senses, this information must be carried to the correct location. The spinal cord is the highway for communication between the body and the brain. When the spinal cord is injured, this information transfer is disrupted.

Sports injuries account for 7% of approximately 11,000 spinal cord injuries a year. Initial hospitalization (an average of 15 days in acute care, then 44 days in rehabilitation), adaptive equipment and home modification costs following injury average $140,000. Additional lifetime costs incurred by spinal cord injury sufferers average $400,000 and can reach as high as $1.35 million depending on the severity of injury and the age at which injury occurrs. Spinal cord injuries cost more than $10 billion yearly.

Because the CNS is so important and cannot repair itself easily, it is proposed to design a personal air bag protection device that can be used by bike/horse riders. The purpose of this paper is to outline the preliminary investigation of the feasibility of such a device. A mock torso was constructed with wood, instrumented and subjected to a 1-meter drop. The impact accelerations were measured for trials with and without a prototype air bag attached to the mock torso to demonstrate the force mitigation capability of the air bag. Using finite element commercial code ABAQUS/Explicit a model of the mock torso was subjected to a simulated 1-meter drop. The model was refined to match the results from the experimental drops without an air bag, and then the analysis was performed with springs and dampers inserted to simulate the air bag.

2 EXPERIMENTAL PROCESS

The purpose of the experimentation was to demonstrate the ability of an air bag to reduce the force experienced during an impact resulting from a fall. To do this, a mock torso was constructed and then subjected to several drop tests while accelerations were recorded.

2.1 EDDIE Description

A model of the human torso was constructed for impact analysis. The major dimensions for the torso were determined by taking approximate width, height, and depth measurements of a 5' 10" male. Standard 2x4 and 2x6 pine lumber, 1/4-inch plywood, wood glue and drywall screws were used to construct the torso. The torso was designed such that when dropped on it's "back" it would land on the protruding 2x6 that forms the "backbone" of the model. Figure 2.1 is a drawing of the model, which was nicknamed EDDIE (Eco-friendly Dynamic Device for Impact Experimentation).

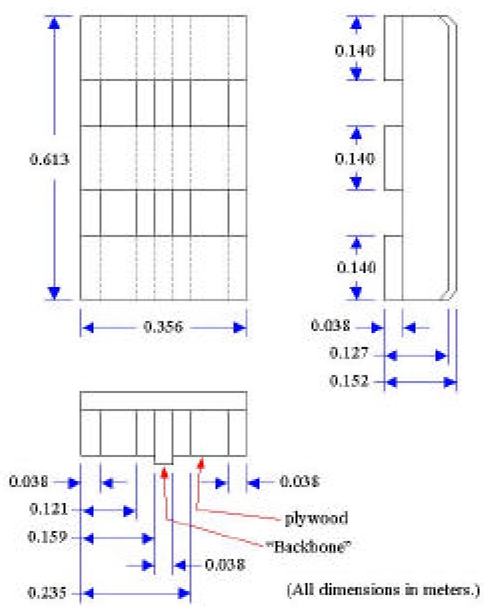

Figure 2.1 EDDIE dimensions

2.2 Air Bag Description

To mitigate the impact seen by the EDDIE model due to a one-meter drop, two air bags were constructed. The outer layer of each bag was constructed of thin nylon material. Deflated, the dimensions of the bag were 25 cm by 58 cm. Inflated, the volume of the bag was approximately 9,350 cubic centimeters. Two separate liners were tested inside the nylon bag. One liner was filled with air and completely sealed from leaking, the other liner was stitched into the bag, thus contained holes that allowed the air to slowly leak out. The air bag was attached to the spinal cord of EDDIE with tape. Once EDDIE was hanging from the one-meter drop height, the bag was inflated and the open end of the bag was taped closed.

2.3 Drop Tower Description

For impact tests on EDDIE, it was necessary to design a system that would allow the model to be suspended a minimum of one meter above the ground and provide a method for a clean release of the model during the drop tests. A wooden frame drop tower, shown in Figure 2.2**,** was designed and built. The drop tower provided a 1.4 by 1.5 meter drop zone area on the floor, and allowed for a maximum drop height of approximately 2.3 meters. EDDIE was suspended from the drop tower by nylon chord which, when cut, allowed EDDIE to drop and impact the floor within the drop zone.

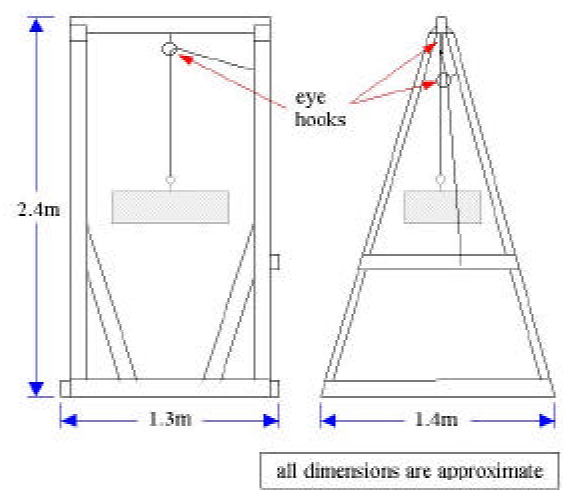

Figure 2.2 Drop Tower dimensions

2.4 Test Setup/Data Acquisition

Preliminary estimates of the impact force that EDDIE might experience from a drop of one meter were calculated. These estimates indicated that EDDIE might experience accelerations on the order of 2000 **g**'s. Therefore, EDDIE was instrumented with four Endevco piezoresistive accelerometers (model 2264A-5K-R) with 5000 **g** ranges. One of the accelerometers was determined to be malfunctioning, so data from only three accelerometers was kept from each test. The accelerometers were attached to aluminum mounting plates that were hot glued to the top of EDDIE.

The accelerometers were connected to a Measurement Division (model 2311) signal conditioner, with the voltage gain on the conditioner set at 10X. This conditioner was then connected to a Nicolet Data Acquisition System oscilloscope, which was running Odyssey, version 2.01, data acquisition software. The software was set to collect data at a frequency of twenty kilohertz.

2.5 Experimental Procedure

A total of six drop tests were performed. Each test involved suspending EDDIE from a height of one meter by a nylon chord; then, on the signal of the data acquisition controller, logs were started on the recording oscilloscope and the nylon chord was cut, allowing EDDIE to fall to the ground. The first two tests involved dropping EDDIE with no 'spinal chord' protection. The second two tests involved dropping EDDIE with the sealed air bag attached to the spinal chord. The final two tests were also air bag tests, but instead of using a sealed air bag, the bag attached to EDDIE was designed to be leaky.

2.6 Test Results

This section contains three plots that represent the acceleration data from the three types of drops that were performed. Each plot shows the average acceleration recorded by the three working accelerometers on a single drop test. The average acceleration for a drop with no air bag is shown in Figure 2.3; Figure 2.4 is the data from a drop with a fully inflated, sealed air bag; Figure 2.5 shows the average acceleration from the drop test with the designed, leaky air bag.

Figure 2.5 shows that the impulse time during impact for the drop with the designed (leaky) air bag was about twice as long as it was for the drop without the air bag, seen in Figure 2.3. This resulted in much lower accelerations during the air bag drop, and therefore EDDIE experienced much lower impact forces. With the leaky air bag, the maximum acceleration experienced by the model was about 1,350 g's during impact from a one-meter drop height. With the leaky air bag, the peak acceleration was reduced to about 40 g's.

The plot from the sealed air bag test, Figure 2.4, indicates that an air bag that is not specifically designed to leak air on impact is not the most effective method to dramatically reduce impulse time and impact forces.

The impulse tests of EDDIE with various degrees of protection reveal the need for a leaky air bag design. With no protection the impulse forces reach peaks of 1000 g's of acceleration. With the sealed air bag the acceleration reaches magnitudes on the order of 250 g's of acceleration. The leaky air bag is the best option, reducing the impulse forces to around 40 g's of acceleration.

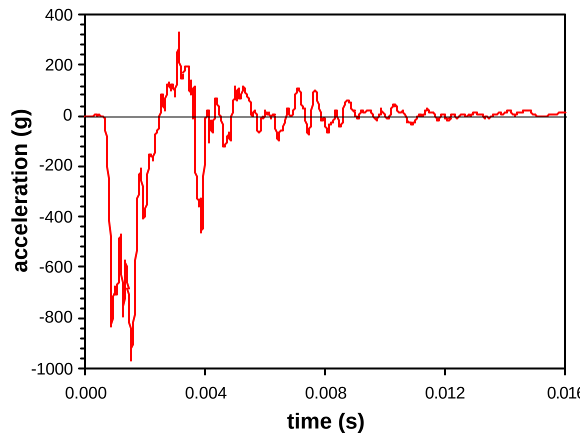

Figure 2.3 Time history of drop test with no air bag

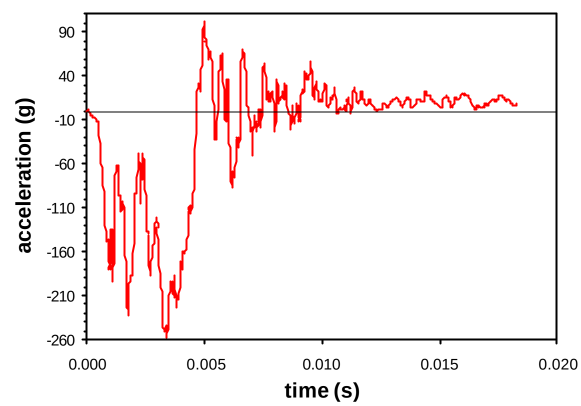

Figure 2.4 Time history of test with sealed air bag

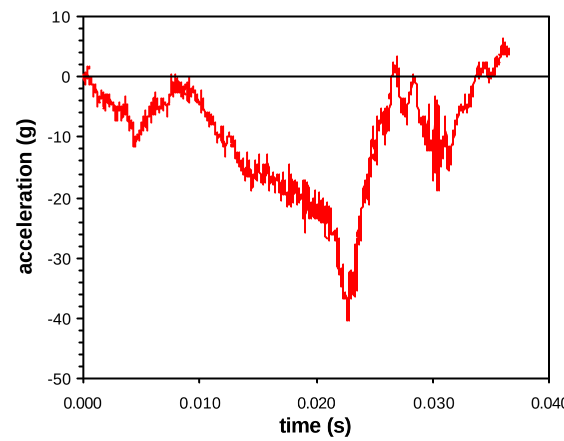

Figure 2.5 Time history of test with leaky air bag

3 FINITE ELEMENT ANLAYSIS

A Finite Element Analysis was performed to verify the experimental results from the drop tests. At first, the analysis was done to match the drop with no air bag. After that model was accurate, springs and dampers were added between the mock torso (EDDIE) and the floor to simulate the air bag. The geometry and mesh for the EDDIE and the floor were constructed using the pre-processor Patran. The commercial code ABAQUS/Explicit was used to perform the finite element analysis.

3.1 The FE Model

The model was constructed with the same geometry as the physical model used in the drop tests, as shown in Figure 2.1. The finite element model has 19,959 degrees of freedom. This includes EDDIE, the floor, the carpet, and the air bag. Figure 3.1 shows the finite element model.

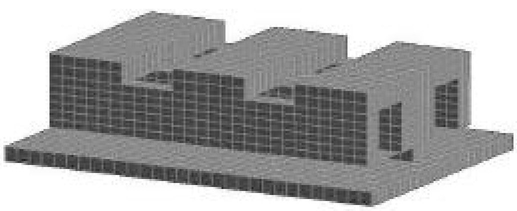

Figure 3.1 Finite Element Model of EDDIE

3.1.1 EDDIE

EDDIE is made up of 2,676 elements: 2,260 8-node linear brick elements and 416 4-node shell elements (which formed the plywood). These elements were originally assigned property values corresponding to the wood used to build the physical model. Then the values were modified slightly to match the results from the model to the experimental results. The density was adjusted so the mass of the model was equal to the measured mass of the physical model. Young's modulus of the wood was lowered to 0.4 GPa from the original value of 9.0 GPa. The significant lowering is due to the fact that EDDIE was made of several pieces of wood that were screwed and glued together. These added joints and surface contacts make the properties of the structure different from the properties of a single piece of material.

3.1.2 Floor

The floor in the model consists of two layers of elements, each layer being 26 elements by 30 elements, for a total of 1,560 elements in the floor model. The top layer is made of 8-node linear brick elements, and the bottom layer is made of 8-node linear, one-way infinite elements. Infinite elements were used on the bottom layer to prevent wave propagation through the floor elements from interfering with EDDIE and altering the impact reactions. The floor elements were assigned material properties of concrete: Young's modulus = 25 GPa, density = 2,320 kg/m^3. Boundary conditions are applied to the bottom layer of nodes of the floor elements. They are constrained from moving in all three directions.

3.1.3 Carpet

The carpet on the floor where the experimental drops were performed was simulated with dashpots in the finite element model. Dashpots were connected between each node along the "backbone" of EDDIE in the model, and the other ends of the dashpots were attached to the nodes on the surface of the floor directly below the "backbone". The damper values were determined by tuning the model to best simulate the experimental results.

3.2 FE Simulated Drop

To simulate the drop from one meter without the air bag EDDIE was given an initial velocity and positioned with the "backbone" touching the floor. The initial velocity was determined by equating the potential energy before the fall with the kinetic energy after falling one meter due to gravity. For the drop without the air bag the velocity at the time of impact is (2 * (9.8 m/s) * (1 m)) ^ (1/2) = 4.4 m/s.

The accelerations were recorded for the nodes located where the accelerometers were attached to the physical model. The analysis without the air bag was run for 4 milliseconds. The plot of the average accelerations for the four nodes is shown in Figure 3.2.

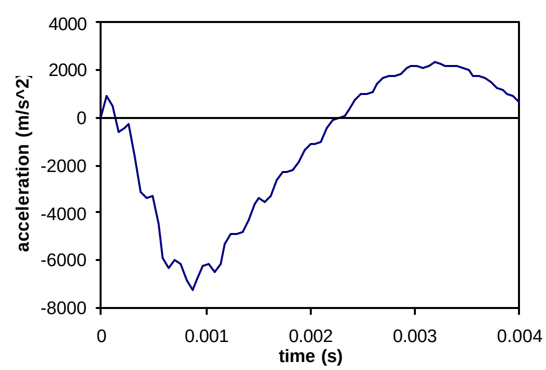

Figure 3.2 Finite Element Model Impact Acceleration With No Air Bag

Figure 3.3 shows the acceleration plot from the finite element analysis and the average acceleration from an experimental drop test. The shape and maximum amplitude of the finite element curve very closely match the experimental curve for the peak of the initial impact and the following rebound.

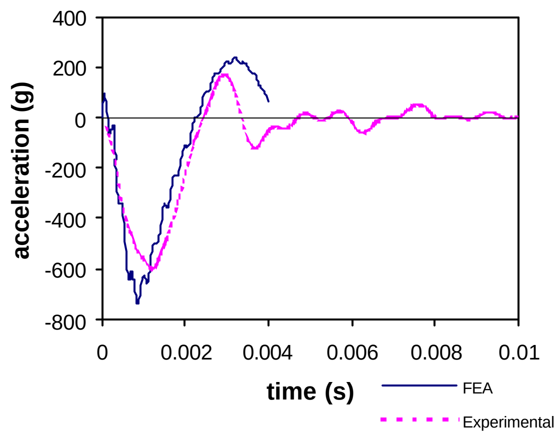

Figure 3.3 FEA and Experimental Impulse Comparison With No Air Bag

3.3 FE Simulated Air Bag Drop

To simulate the drop with the air bag, EDDIE was moved away from the floor, and springs and dampers were added between EDDIE and the floor. In the model, EDDIE was raised 6 centimeters, which is approximately the thickness of the physical air bag. A spring element and a dashpot element were attached to each node on EDDIE's "backbone" and to the corresponding nodes on the floor surface (in the same places as the carpet dashpots). The damper values and spring constants were determined by again tuning the model results to the experimental results. The dashpot values were set to be a nonlinear function of the velocity so they would resist motion while the model was “falling” and not after the impact. The plot of the average accelerations for the finite element model is shown in Figure 3.4.

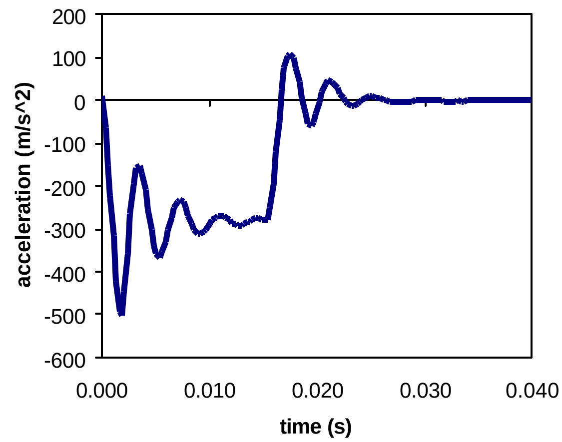

Figure 3.4 Finite Element Model Impact Acceleration With Simulated Air Bag

Figure 3.5 shows the acceleration plots for the experimental air bag drop and the finite element model with the simulated air bag. The plots don’t correspond exactly, but the average magnitudes of the first peak are close to the same. The impact times for the experiment and the model also match closely. To get better correlation, the spring and damper values in the finite element model would need to be more finely tuned, or a more sophisticated air bag model could be developed.

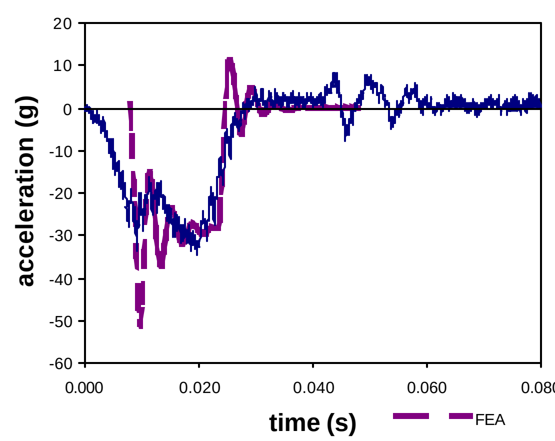

Figure 3.5 FEA and Experimental Impulse Comparison With Air Bag

4 DESIGN PROPOSAL

The spinal cord is more protected than any other organs in the body. The main line of defense is the bone of the skull and vertebra, which makes a hard, tough, physical barrier to protect the brain and spinal cord from injury. Just below the bone is a fluid filled space to provide shock absorbance. The most common type of spinal cord injury is the result of concussive trauma, which accounts for approximately 35% of injured spinal cords. In this case, the spinal cord is not severed. Instead, an impact leaves the soft tissue of the spinal cord bruised and damaged, leading to bleeding from local blood vessels and swelling of the cord inside the vertebra. The goal of our spinal cord trauma mitigation device is to reduce the shock subjected to the spinal cord during a fall. This proposal will outline the main issues associated with the design, including:

?? Ergonomics/geometry associated with the inflated/un-inflated air bag

?? Transducers and data processing required to detect a fall and initiate the deployment of the air bag

?? Deployment and inflation of the air bag

4.1 Ergonomics/Geometry

Comfort and protection are the competing elements in determining the design of the air bag. The air bag must not be obtrusive as to hinder the performance of the athlete, however, its range of protection must be inclusive of the Cervical, Thoracic, and Lumbar Spinal regions. This would require the inflated air bag to transcend from the pelvis all the way up the back and around both sides of the neck. A shirt with a lining that contained a folded air bag that ran along the spine would be ideal. When a possible trauma situation is detected the air bag would deploy.

4.2 Transducers/Data Processing

There are a variety of ways that the air bag could sense a possible trauma situation. This is by far the most ambiguous and challenging design parameter. Possible methods of sensing dangerous situation are the use of accelerometers to detect out of range acceleration and/or the use of proximity transducers to detect the position and speed relative to the impact surface. By far the simplest and most practical detection mechanism would be a tether that would be severed if a rider fell of their bike. This could be coupled with either the accelerometers and/or the proximity sensors.

The use of accelerometer would require substantial preliminary work. A rider, whom produces a variety of random accelerations, could unintentionally deploy the air bag if correct data acquisition and analysis algorithms were not developed. This would require a thorough investigation to determine the signal characteristics of acceleration that could be potentially dangerous.

The use of proximity sensors would probably be a more practical solution. Various types are readily available that are both economical and compact. Ultrasonic and optical sensors are ideal choices, each containing its respective positive and negative attributes. The measurement of displacements can be made using either of these methods, which use the principles of wave interference. In general, waves from a source are transmitted and reflected, and the intensity of the resulting wave is measured. Depending on the phase shift of the waves, they will either add or subtract and the intensity of the measured waves will vary. Displacement measurements can be made by electronically comparing the intensity of the measured wave to a reference wave intensity. This could effectively measure both the distance and speed of a rider relative to an impact surface.

Coupling a tether with a displacement sensor or accelerometers could provide a more fail safe and practical way of detecting a potentially dangerous event. If a rider were to fall off their bike a tether would separate and arm the deployment device. Then if an unacceptable acceleration or displacement and velocity were detected the air bag deployment device would inflate the air bag.

4.3 Deployment

The chief technical hurdle involved in the deployment of an air bag is the storage and release of compressed air. Carrying around a can of compressed air is both dangerous and impractical. A vast amount of technology has evolved over the last two decades for the deployment of automotive air bags. This technology is becoming readily available and inexpensive. Automobile air bags use small solid-propellant inflators. Air bags are actually inflated by the equivalent of a solid rocket booster. Sodium azide (NaN_3) and potassium nitrate (KNO_3) react very quickly to produce a large pulse of hot nitrogen gas. This gas inflates the bag, which literally bursts out of the steering wheel as the bag expands. Within a second of deployment the bag is already deflating through small holes in its back surface. This leaky design is ideal for our application. Successive experiments revealed the advantages of having a leaky air bag. The impulse accelerations were decreased by factors of ten or more when an air bag that had holes was used instead of one that had constant volume.

5 CONCLUSION

The drop tests of EDDIE were successful in demonstrating that an air bag device can greatly reduce impact forces resulting from a fall. EDDIE was also successfully modeled in ABAQUS and with a few adjustments and additions the finite element model can be used to simulate a wide variety of drop tests including angled falls, falls with angular velocities, falls from higher distances, and falls onto other surfaces. This will be beneficial in analyzing new air bag designs and determining desirable properties of the air bag. Ultimately a prototype air bag system could be designed within ABAQUS and thoroughly tested before money is invested in building a physical prototype.

ACKNOWLEDGEMENT

This project was completed as part of the Los Alamos Dynamic Summer School at Los Alamos National Laboratory. Funding for the program came from the United States Department of Energy.

REFERENCES

[1] Hibbitt, Karlsson & Sorensen, INC., *ABAQUS/Explicit User's Manual*, Version 5.8, 1998.

[2] http://www.apacure.com/